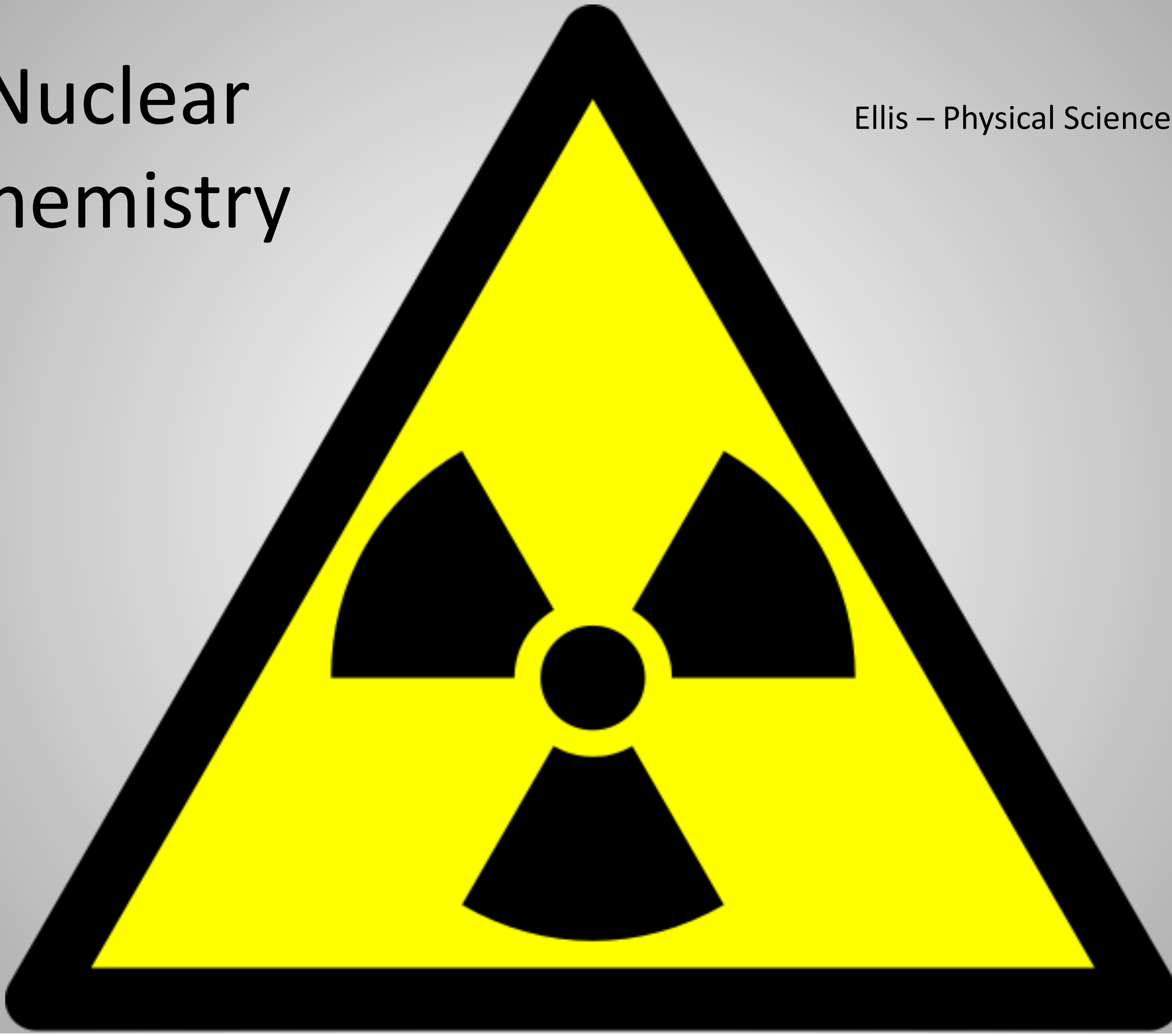
Nuclear Chemistry

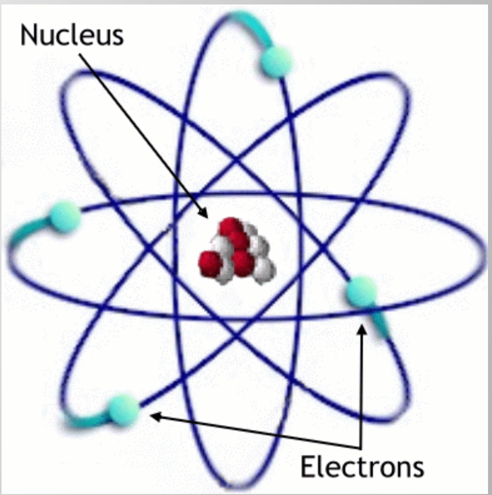


Ellis – Physical Science

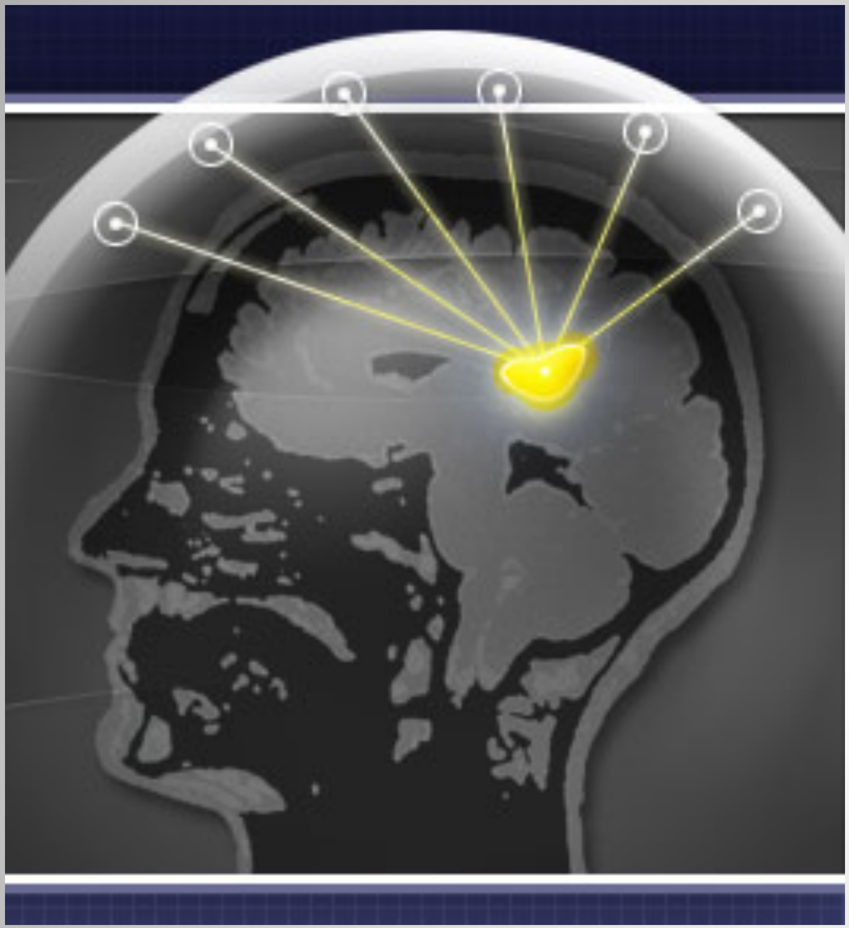
What is Nuclear Chemistry?

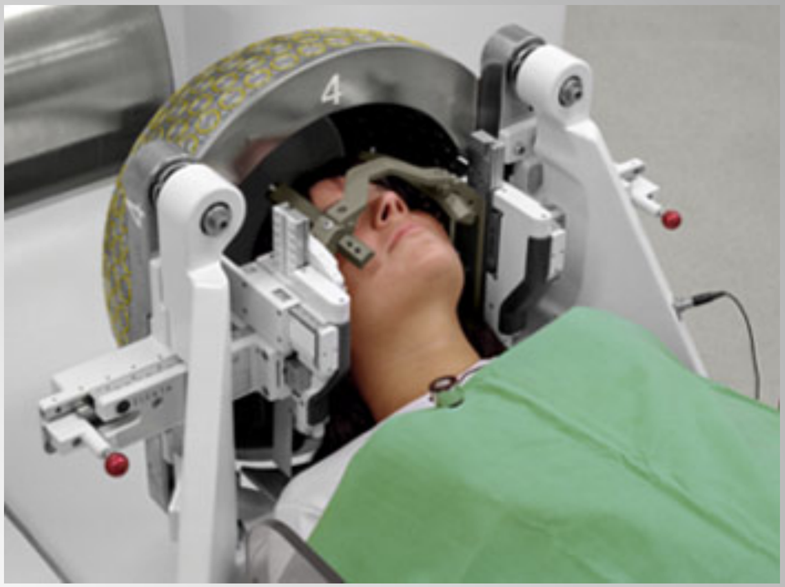
- Nuclear chemistry – subfield of chemistry dealing with radioactivity and nuclear processes, properties and reactions

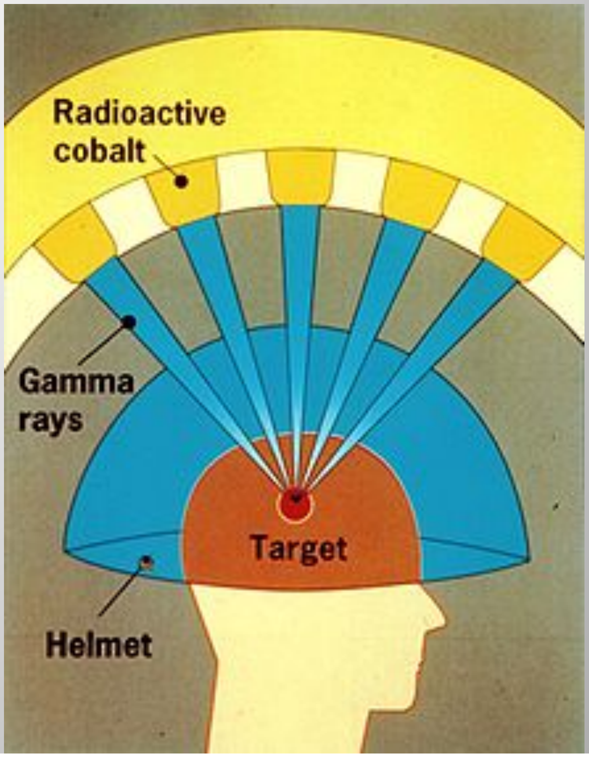
- "Nuclear" = involving the nucleus



Why Do You Care About Nuclear Chemistry? (and believe me, you do)

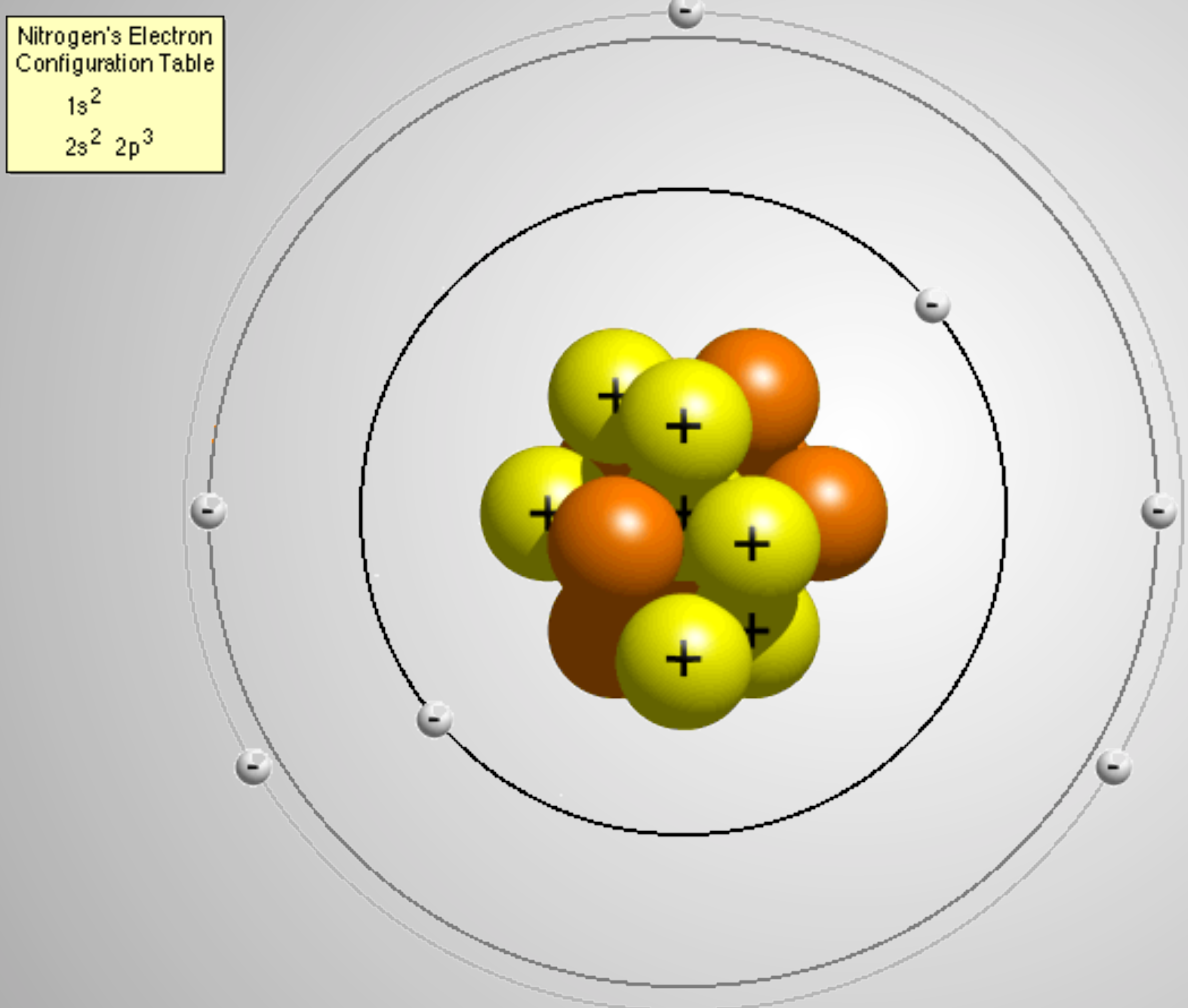






Gamma Knife for inoperable brain tumors and leisions

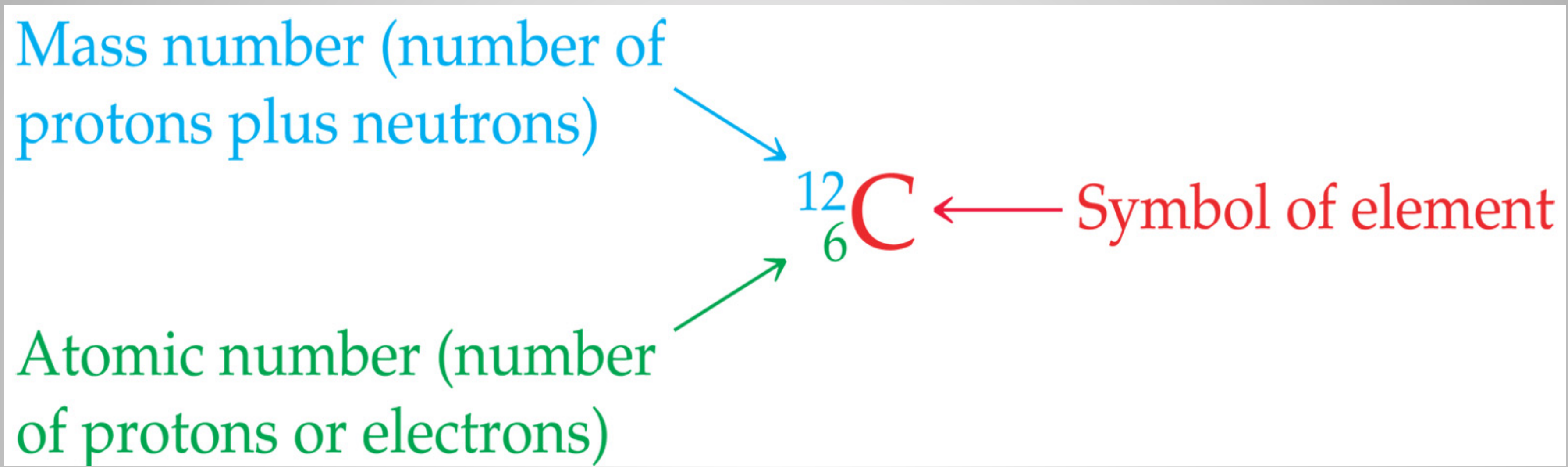
Review



This is an atom of what element?

How do you know?

The Nucleus



- The nucleus is comprised of protons and neutrons (called nucleons).
- The number of protons is the atomic number.
- The number of protons and neutrons together is effectively the mass of the atom.

Isotopes

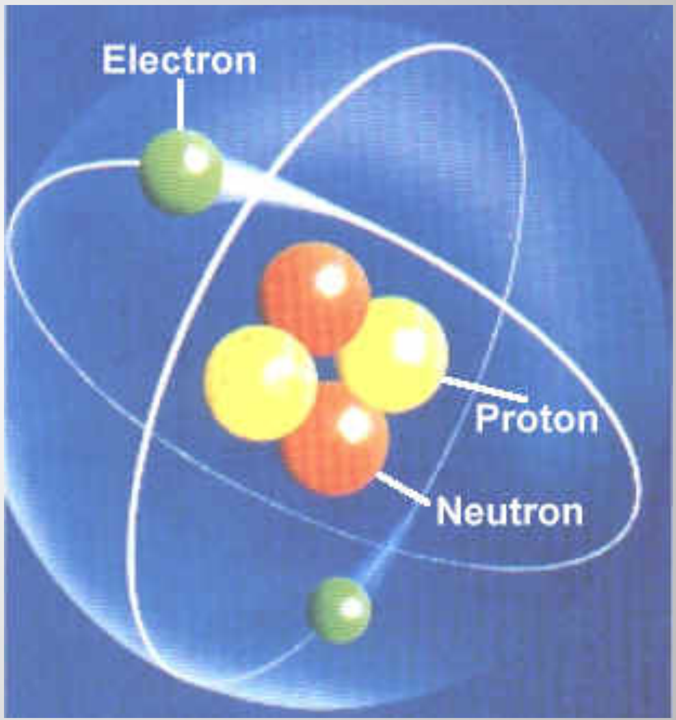
- Not all atoms of the same element have the same mass due to different numbers of neutrons in those atoms.
- For example, the following are three naturally occurring isotopes for uranium (U):
  - Uranium-234
  - Uranium-235
  - Uranium-238

How many neutrons does each isotope of Uranium have?

Nuclear Reactions vs. Normal Chemical Changes

- Nuclear reactions involve the nucleus (protons and neutrons) while "normal" chemical reactions involve electrons

- No matter which type of reaction or change, atoms like to become **STABLE**.



Stability of Atoms

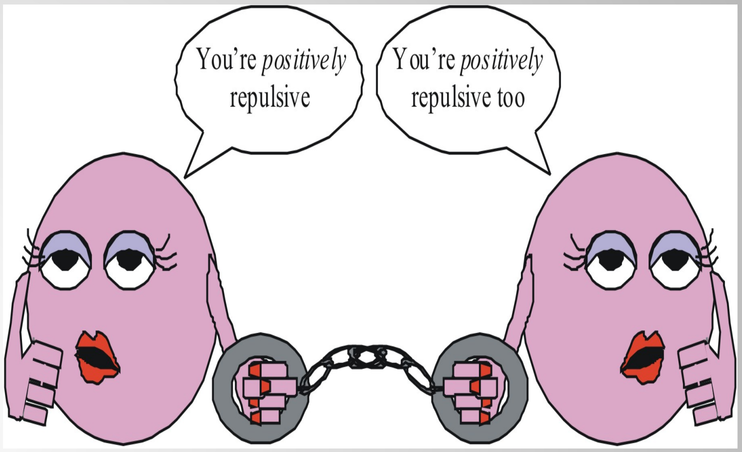
- In a chemical reaction or in bonding, atoms achieve stability by filling their valence electron shells (donate, accept, or share electrons)

- In nuclear reactions, atoms achieve stability by changes to their nuclei (emitting radiation)

What holds an atom together?

TWO Forces→

1. Electrostatic forces



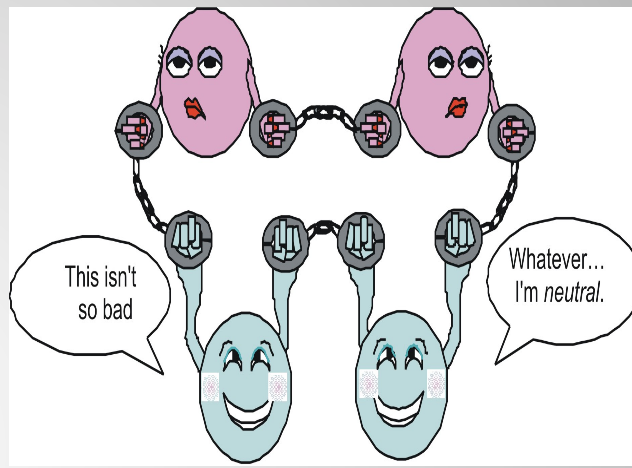
- Attraction and repulsion between charged (e^- and p^+) particles
- Ex. e^- and p^+ = attract
  p^+ and p^+ = repel
- Strength: Short distances = strong
  Long distances = weak
- Any element with more than one proton (i.e., anything but hydrogen) will have repulsions between the protons in the nucleus.

Electrostatic Force

What holds an atom together?

TWO Forces→

2. Strong Nuclear force-



- Attraction between

particles in nucleus

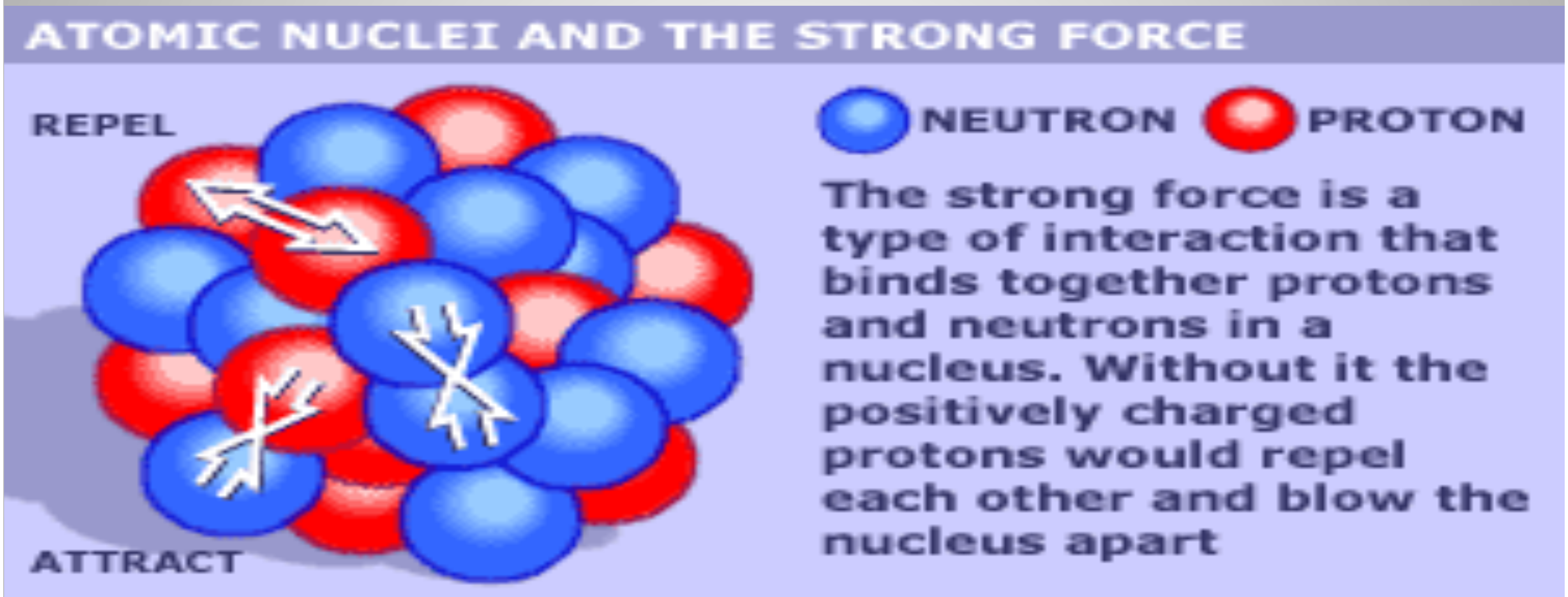
- Strength:

    Short distances = very strong

    Long distances = none

- The strong nuclear force helps keep the nucleus from flying apart.

STRONG NUCLEAR FORCE



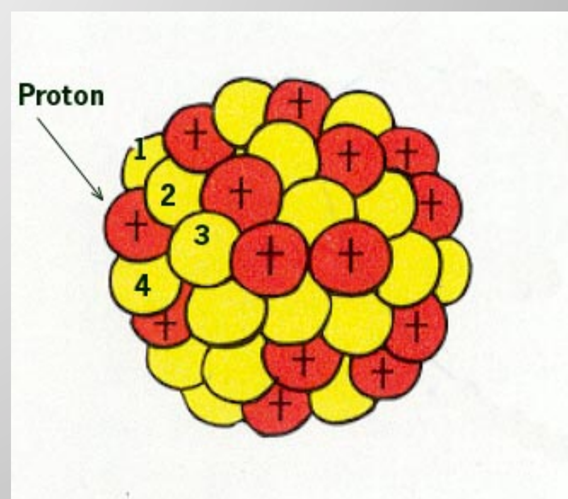
The Importance of Neutrons

- Neutrons play a key role in stabilizing the nucleus.
- Therefore, the ratio of neutrons to protons

is an important factor.

For smaller atoms (*Atomic Number* ≤ 20), stable nuclei have a neutron-to-proton ratio close to 1:1.

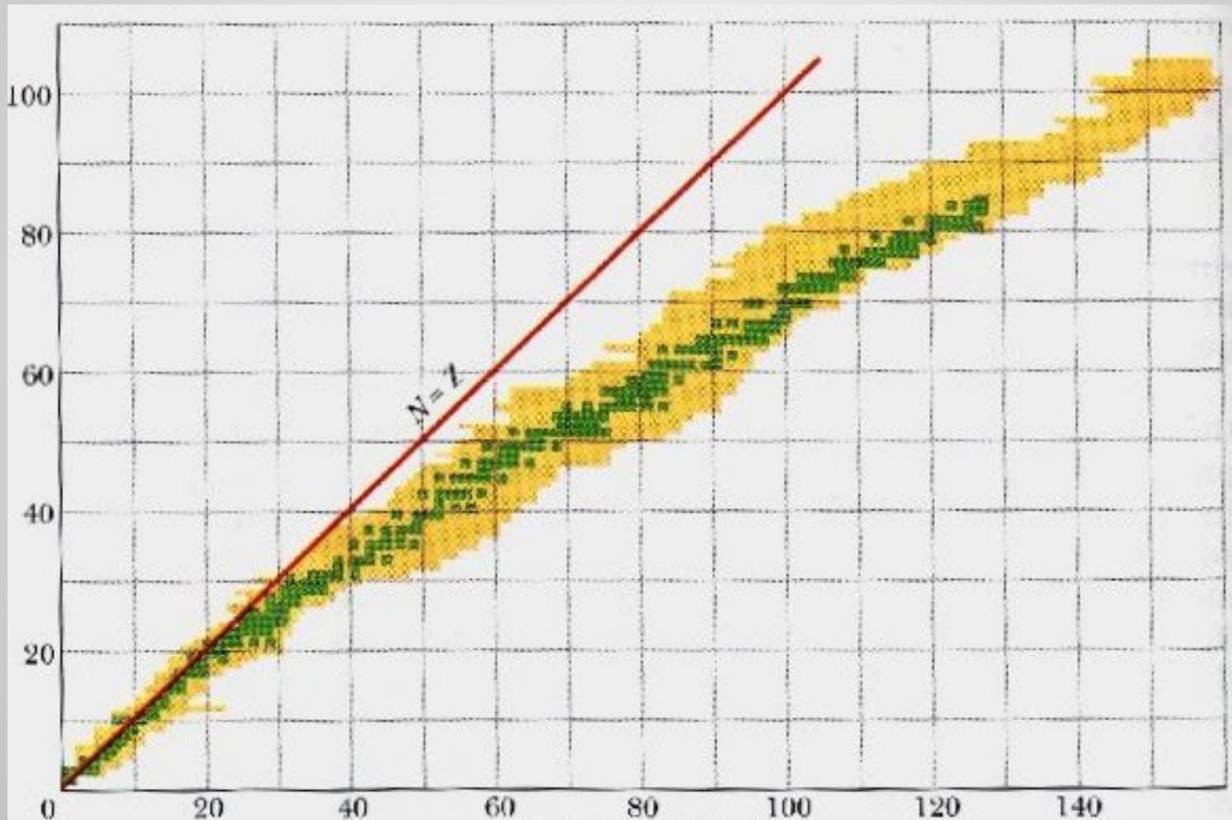
As nuclei get larger, it takes a greater number of neutrons to stabilize the nucleus.



Neutron-Proton Ratios

Anything lying below the “stable region” with too many neutrons will emit parts of the nucleus in order to become stable.

Neutron-Proton ratio for elements of the periodic table

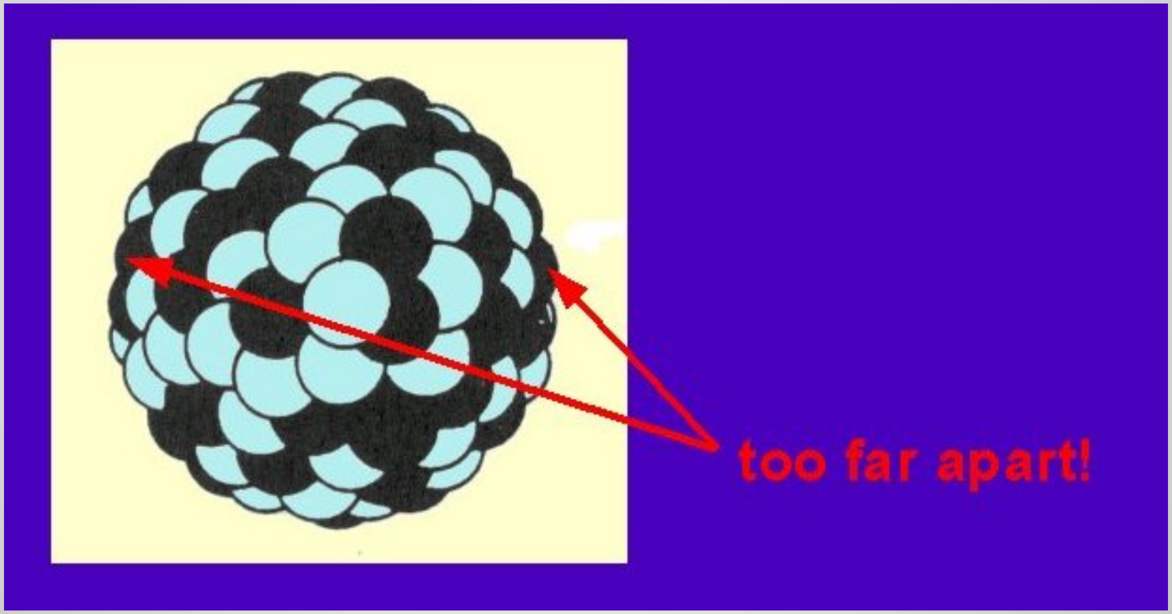


Number Protons

Number Neutrons

Stable Nuclei

- There are no stable nuclei with an atomic number greater than 83.



The strong nuclear force diminishes as the nuclei become larger, but the electrostatic forces are just weaker. Without the strong nuclear force holding the nuclei together, electrostatic forces take over, like charges repel, and the nucleus decays, emitting radiation

Radiation

- Unstable nuclei are "radioactive," meaning they emit radiation
- Radiation – the particles that are released from the nucleus during radioactive decay
- Radioactive decay – breakdown of an unstable atomic nucleus into one or more different nuclides

Types of Radioactivity Decay

- During emission, the atom can change into a different atom OR a different isotope.
- There are several ways nuclei can decay.
- We will focus on:

  Alpha Radiation

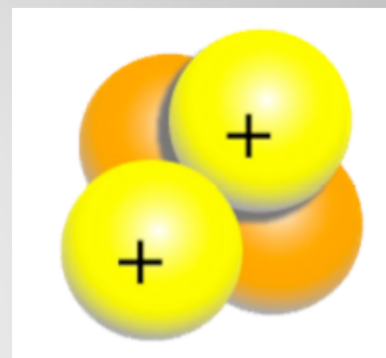
  Beta Radiation

  Gamma Radiation

Alpha Decay

Loss of an α-particle (a helium nucleus, no electrons)

$${}^{4}_{2}He$$



- Least penetrating
- Largest and slowest form of radiation
- Can be stopped by a piece of paper or clothing
- Deadly if released by atoms inside your body
- Common in elements with atomic numbers > 83

$${}^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

Alpha Decay Example

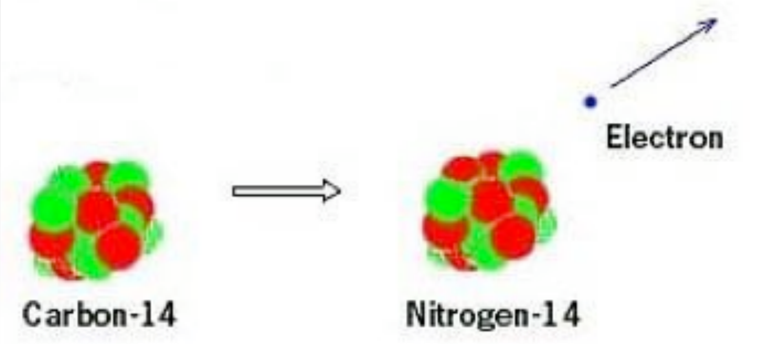
$$^{244}_{94}Pu \longrightarrow \; ^{240}_{92}U + \; ^{4}_{2}He$$

$$^{234}_{90}Th \longrightarrow \; ^{230}_{88}Ra + \; ^{4}_{2}He$$

Beta Decay

-Neutron decays into a proton and an electron representing the loss of a β-particle (a high energy electron)

$${}^{0}_{-1}\beta \quad \text{or} \quad {}^{0}_{-1}e$$



-The proton form stays in the nucleus forming an element with an atomic number 1 greater than the original

-More penetrating and much faster than Alpha particles

-Can be stopped by a sheet of Al foil.

-Common in elements with a high neutron-to-proton ratio, which are below the stable region

$${}^{131}_{53}I \longrightarrow {}^{131}_{54}Xe + {}^{0}_{-1}e$$

Beta Decay Example

$$^{84}_{35}Br \longrightarrow {}^{84}_{36}Kr + {}^{0}_{-1}e$$

$$^{234}_{90}Th \longrightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e$$

Gamma Emission

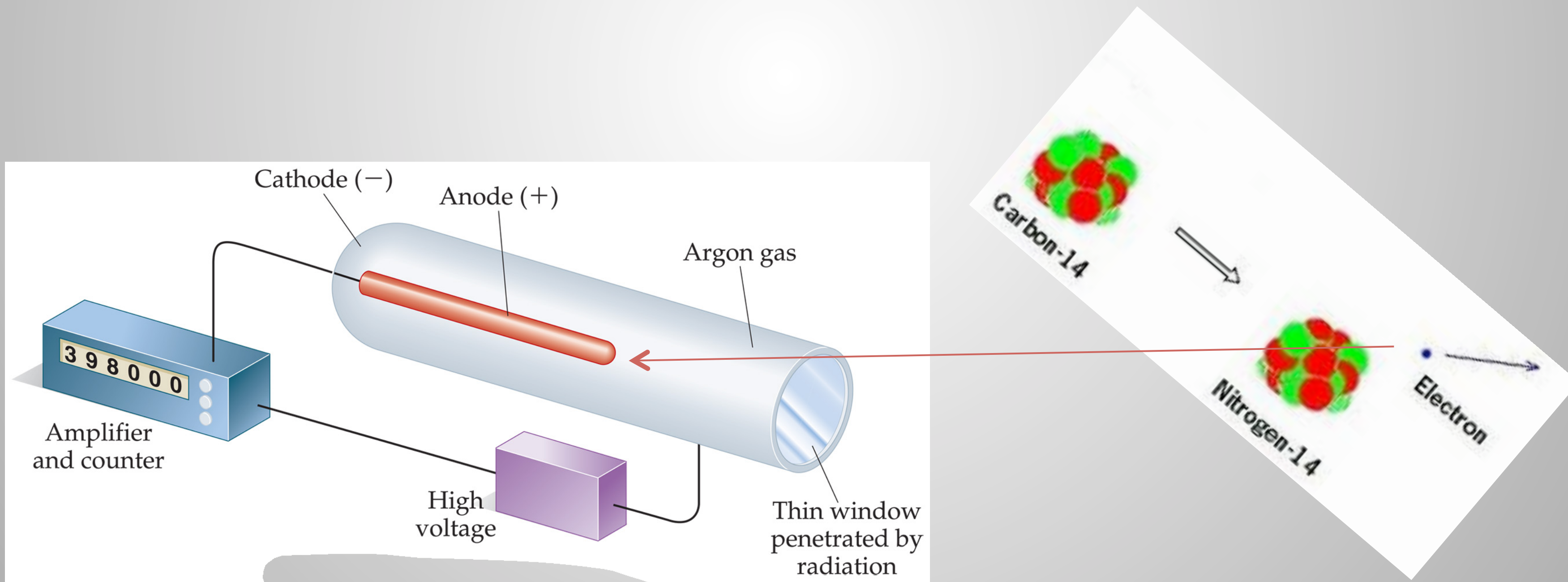
Loss of a γ-ray (high-energy radiation that almost always accompanies the loss of a nuclear particle)

$${}^{0}_{0}\gamma$$

-No mass and no charge
-Emits light with high energy (not matter)
-Travels at speed of light
-Most penetrating
-Lead and concrete are used as barriers

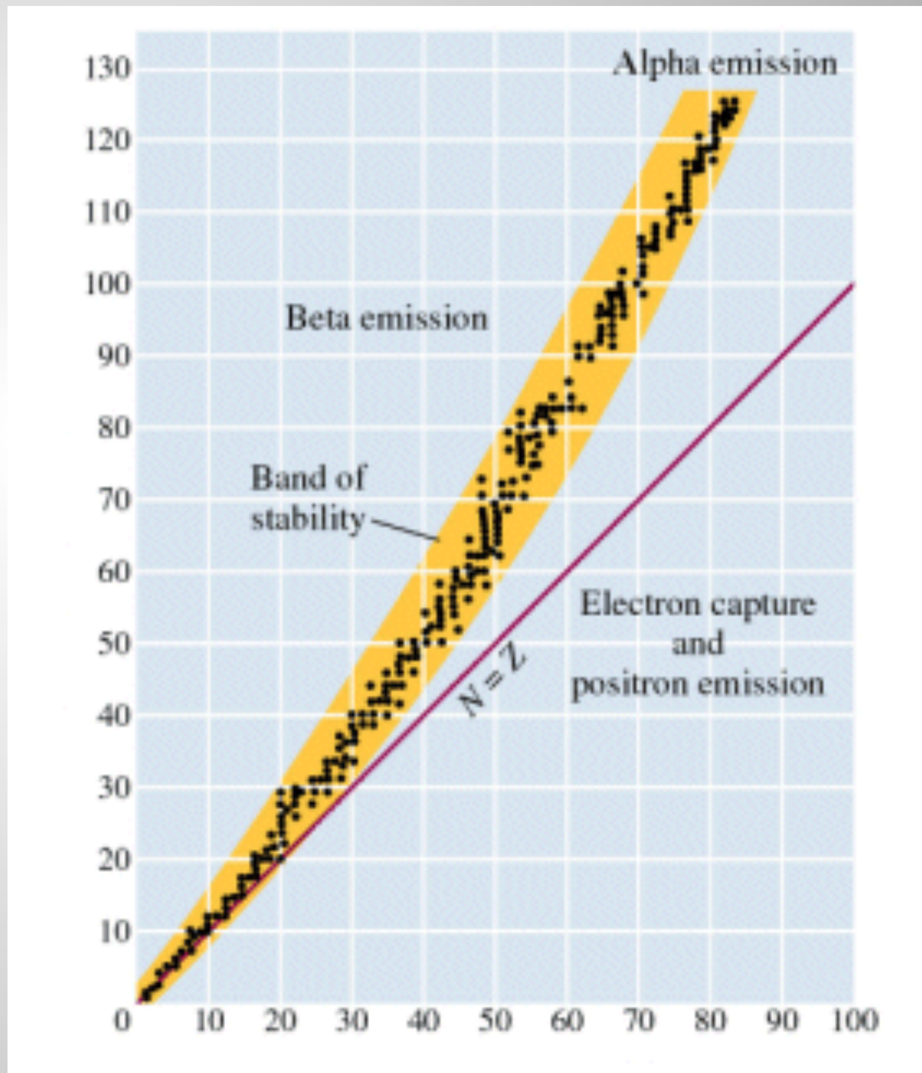
Measuring Radioactivity

- One can use a device like this Geiger counter to measure the amount of activity present in a radioactive sample.



Radioactive Decay Rates

- Radioactive decay depends on the proton to neutron ratio. An atom is generally stable if the ratio is about 1:1



Radioactive Decay Rates

- Half-life: the time in which half of a radioactive substances decays

- Different isotopes have different half-lives; some are nanoseconds and others are billions of years

Common Radioactive Isotopes

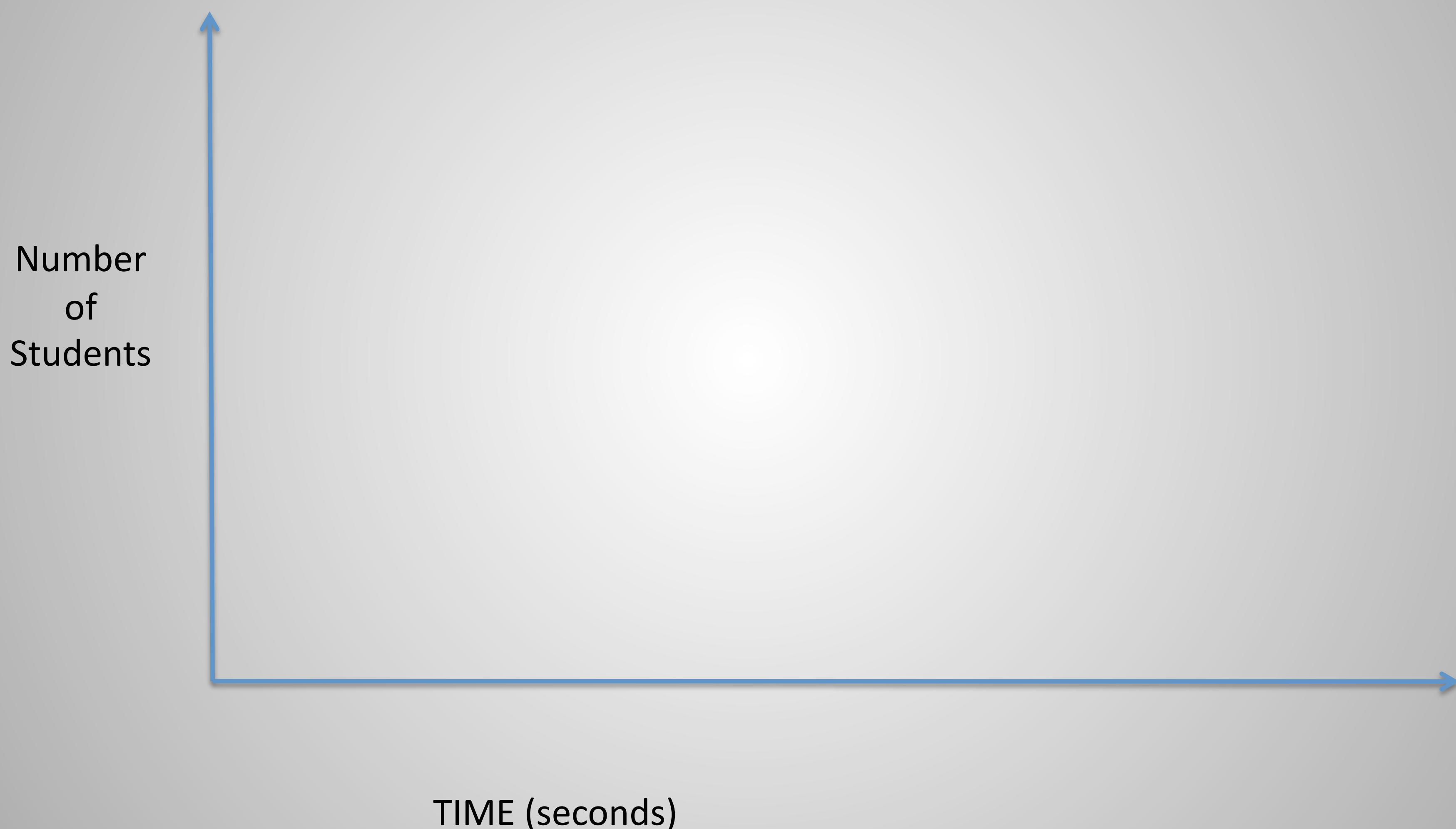
Isotope	*Half-Life*	*Radiation Emitted*
Carbon-14	5,730 years	β, γ
Radon-222	3.8 days	α
Uranium-235	7.0×10^8 years	α, γ
Uranium-238	4.46×10^9 years	α

How does half-life work?

- Classroom Example: half life = 30 seconds

	Time = 0 s	Time = 30 s	Time = 60 s	Time = 90 s	Time = 120 s
Number of Students					

Now Graph the Classroom Data



Radioactive Half-Life

- After one half life there is 1/2 of original sample left.
- After two half-lives, there will be 1/2 of the 1/2 = 1/4 the original sample
- After three half-lives, there will be ½ of ½ of ½ = 1/8 of the original sample

Radioactive Half-Life

- What fraction of the sample will be left after "n" half- lives?

- $(1/2)^n$

- Example: What fraction of the original sample will be left after 4 half lives?

Radioactive Decay Rates

- Use of isotopes with known half-lives:

1. Geologists calculate the age of rocks
2. Archaeologists determine the age of fossils and artifacts
3. Nuclear medicine – common example is the radioactive isotope of iodine to destroy ill performing thyroids

Half-Life Practice Problems

- Radium-226 has a half-life of 1599 years. How long will 7/8 of a sample of radium take to decay?

Half-Life Practice Problems

- A sample of strontium-90 is found to have decayed to 1/8 of its original amount after 87.3 years. What is the half-life of strontium-90?

Transmutation

- Process of changing one element to another through nuclear decay.
- Isotopes that give off alpha and beta particles undergo transmutation.

$$^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

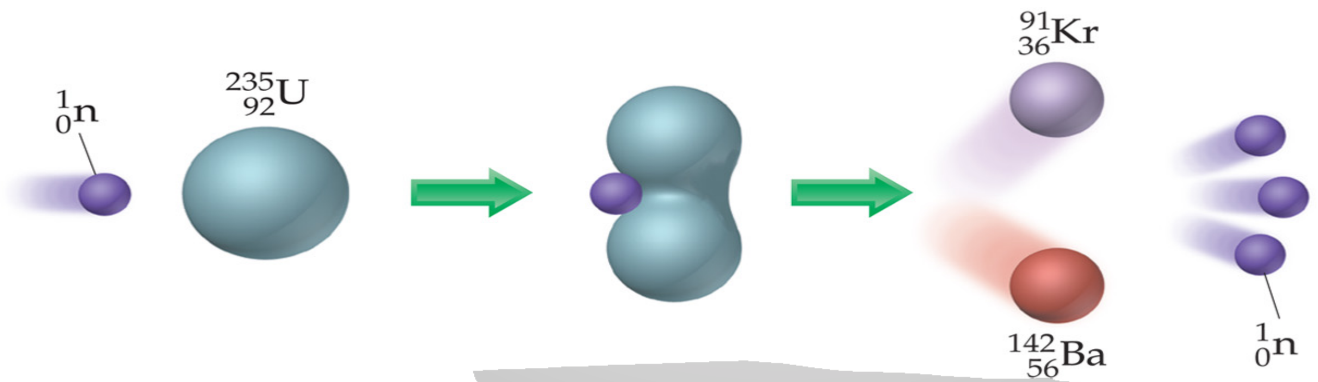
Energy in Nuclear Reactions

- There is a *tremendous* amount of energy stored in nuclei.
- In *chemical* reactions the amount of mass converted to energy is minimal.
- However, these energies are many thousands of times greater in nuclear reactions.

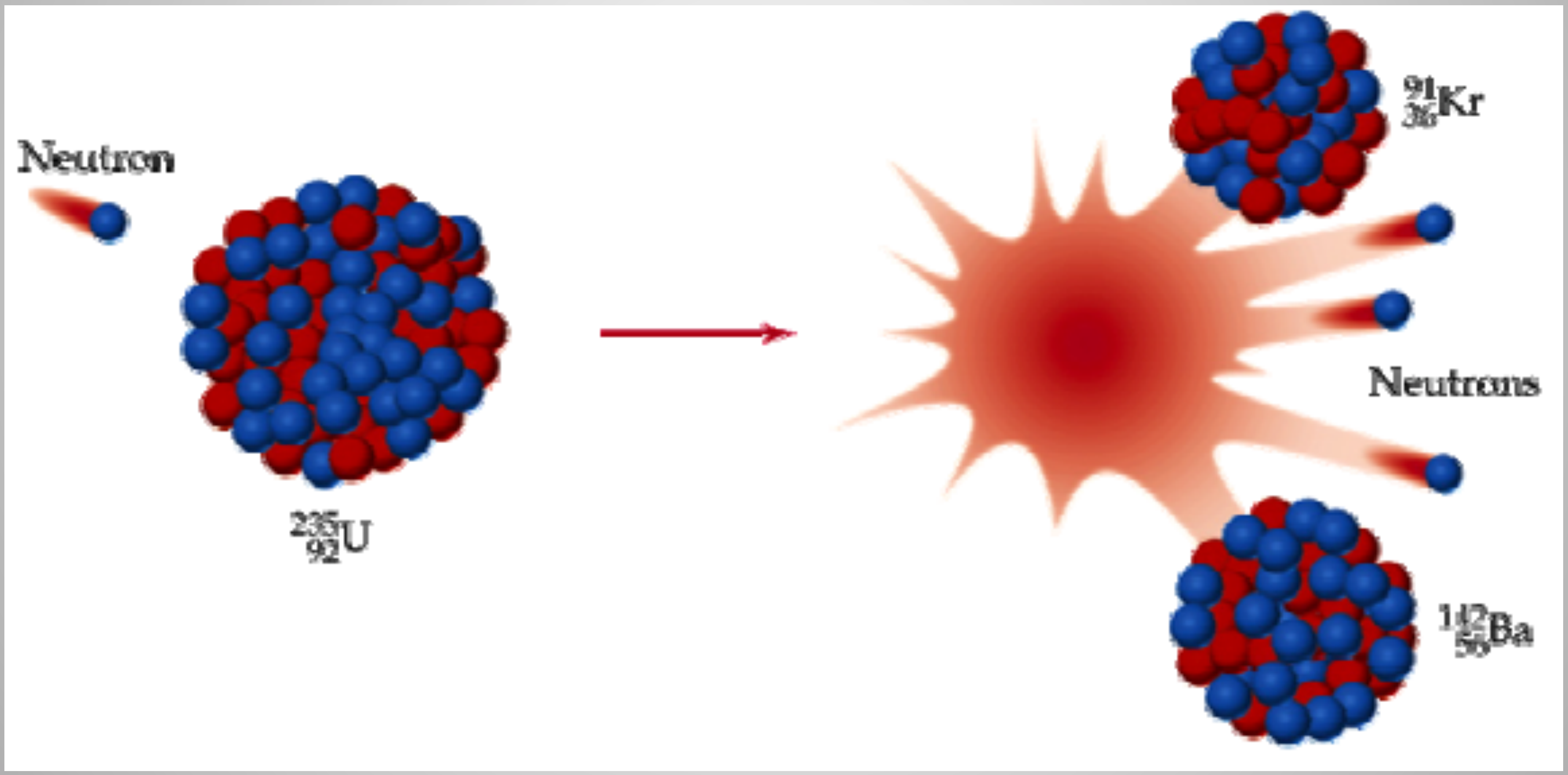
Example: 1 atom splitting is 6,700,000 x's more energetic than ONE molecule of TNT exploding.

Nuclear Fission

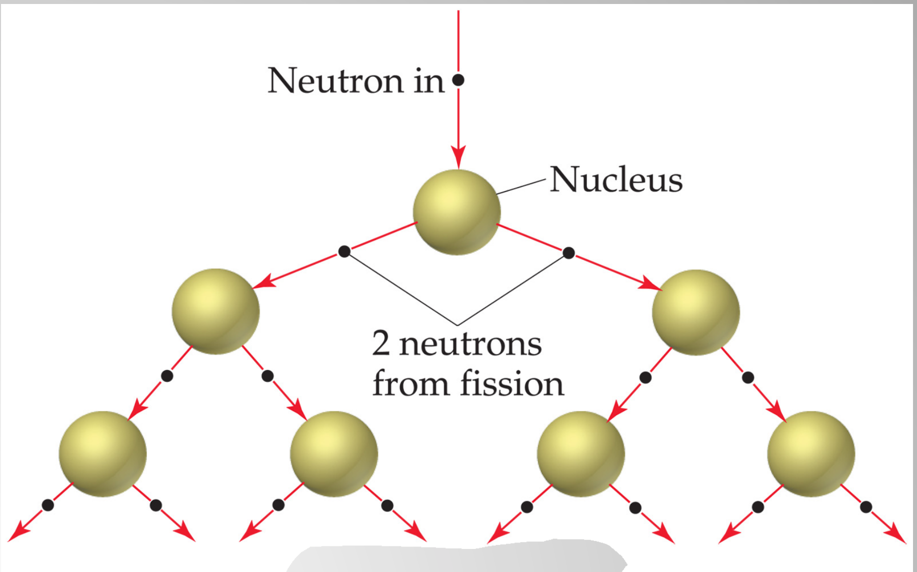
- Nuclear fission is the type of reaction carried out in nuclear reactors to harness this energy.
- A neutron is used to bombard a heavy nucleus, which causes a split of that nucleus into 2 fragments, a release of neutrons, and a release of energy.



Nuclear Fission

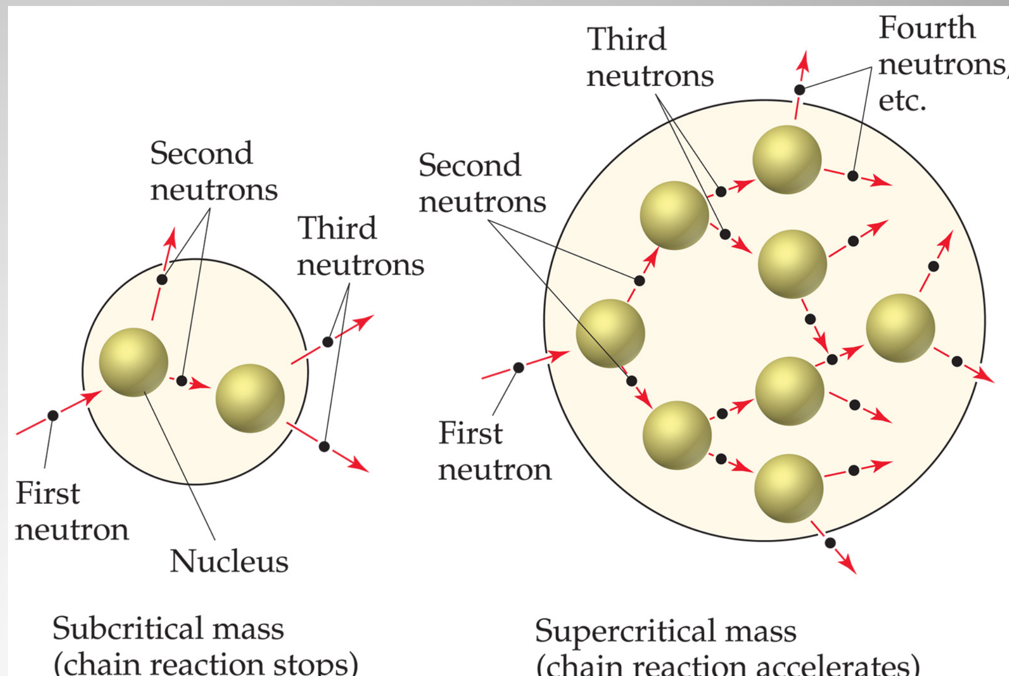


Nuclear Fission can lead to a nuclear chain reaction.



- The neutrons released in a chain reaction can start a chain reaction.
- The neutrons released in the transmutation process can strike other nuclei, causing their decay and the production of more neutrons.
- This process continues in what we call a nuclear chain reaction.

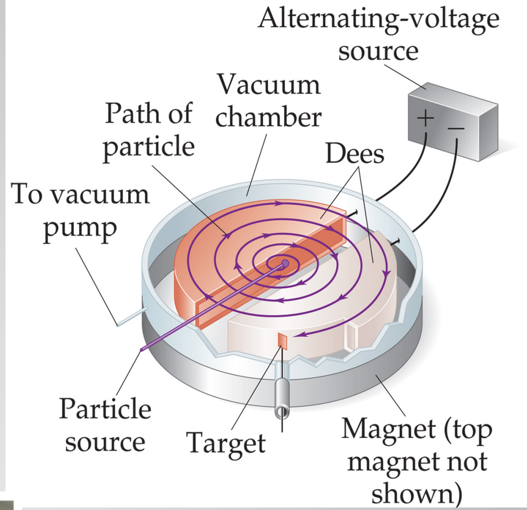
Chain reactions must be sustained with a critical mass



- If there are not enough radioactive nuclides in the path of the ejected neutrons, the chain reaction will die out.
- Therefore, there must be a certain minimum amount of fissionable material present for the chain reaction to be sustained: Critical Mass.

Nuclear Transmutations

Nuclear transmutations can be induced by accelerating a particle and colliding it with the nuclide.

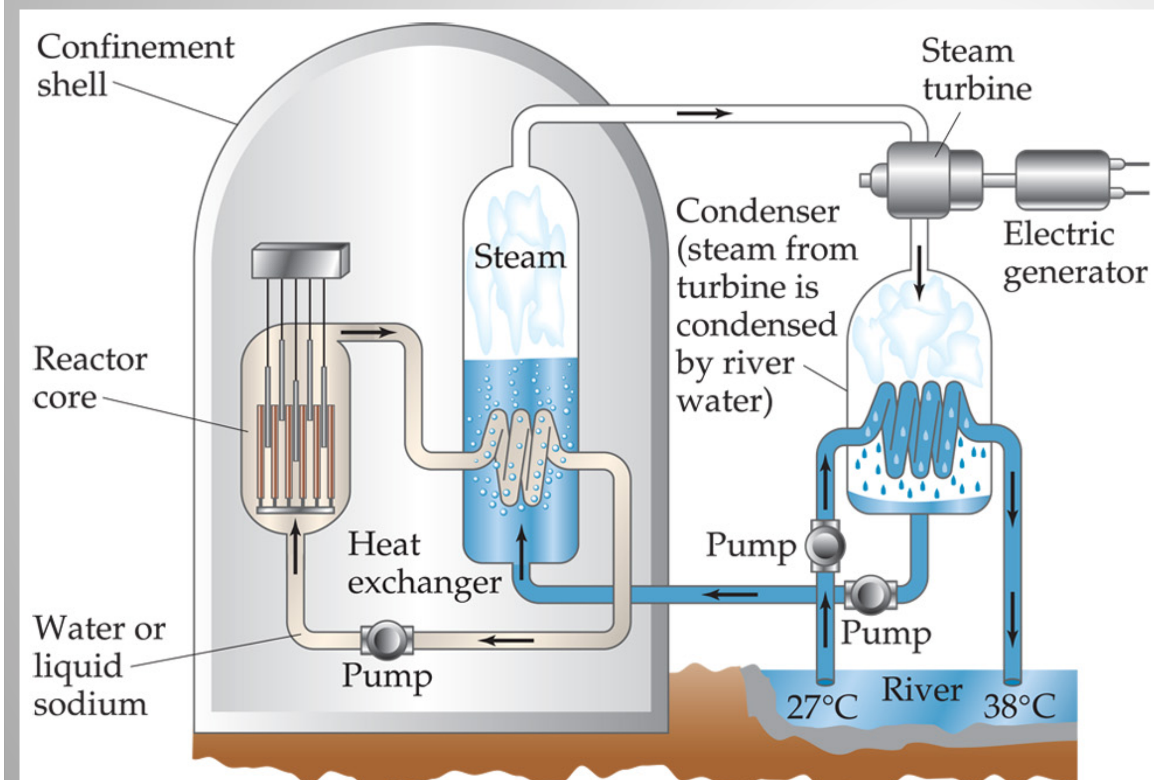


←Tevatron Fermilab

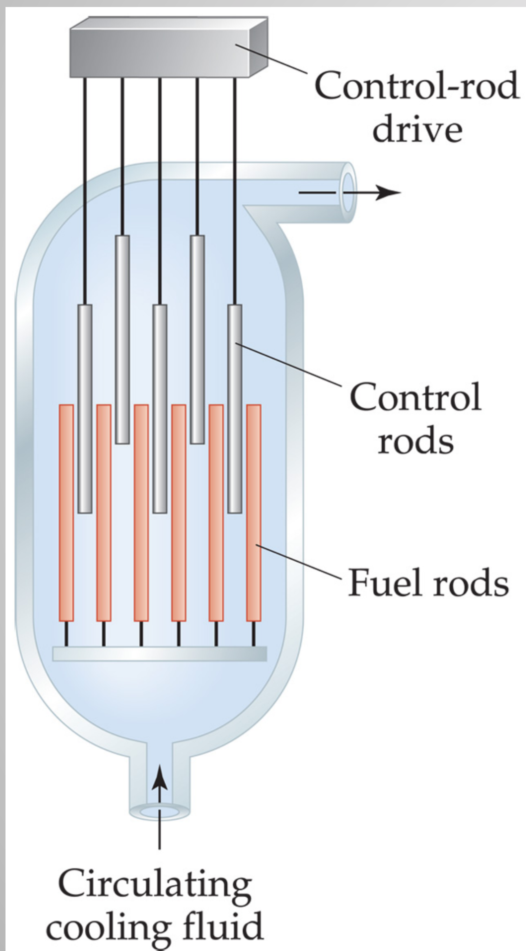
These particle accelerators are enormous, having circular tracks with radii that are miles long.

Nuclear Reactors

In nuclear reactors the heat generated by the reaction is used to produce steam that turns a turbine connected to a generator.



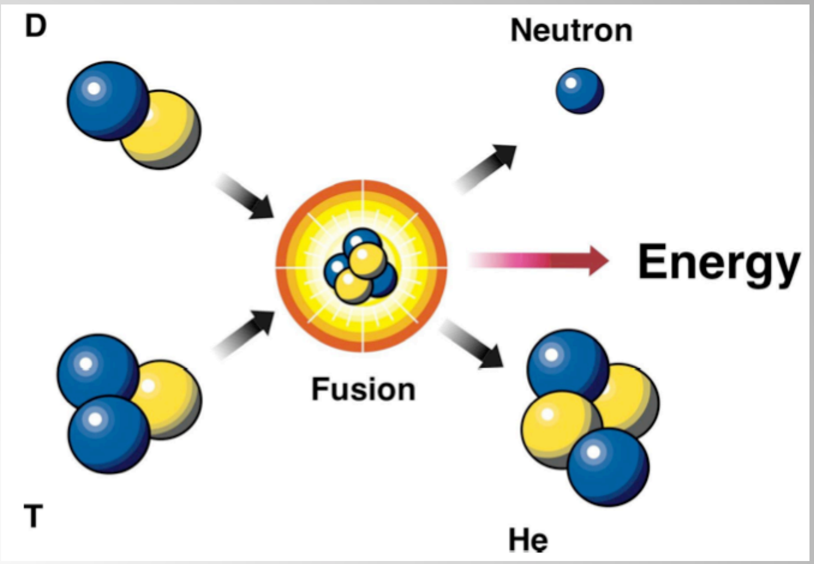
Nuclear Reactors



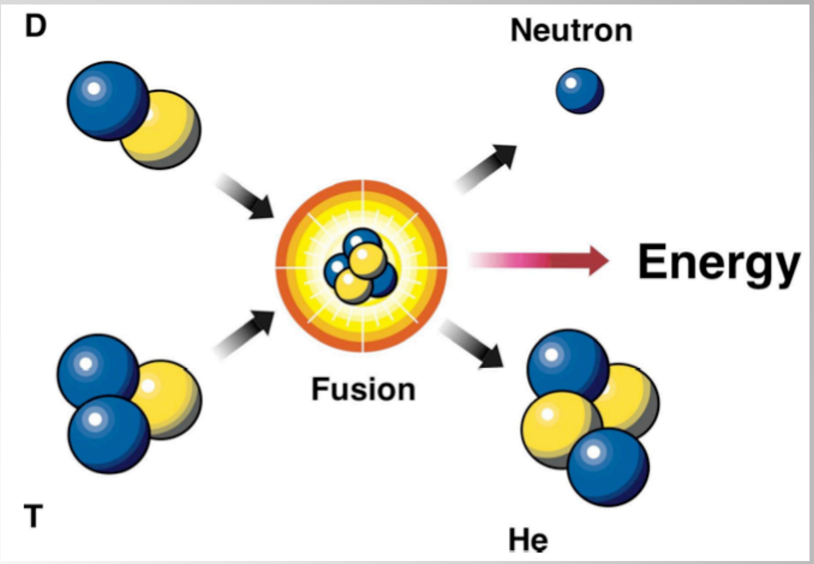
- The reaction is kept in check by the use of control rods.
- Control rods absorb the neutrons and electrons to slow the nuclear reaction process.

Nuclear Fusion

- 2 light nuclei combine to form a heavier nuclide releasing LOTS of energy.
- Fusion powers the stars (including the sun)



Nuclear Fusion



- Fusion would be a superior method of generating power.
  - The good news is that the products of the reaction are not radioactive.
  - The bad news is that in order to achieve fusion, the material must be in the plasma state at several million Kelvins.

Room temperature = about 23 Kelvins.

Nuclear Radiation Today

- You are exposed to nuclear radiation everyday. Some forms are harmful, others beneficial

- Background radiation – the nuclear radiation that arises naturally from the sun, soil, rocks, and plants

- About 80% of our daily exposure comes from these sources…the other 20% comes from human-made sources (computers, smoke detectors, X-Rays)

Nuclear Radiation Today

- Levels of radiation absorbed by the human body are measured in rems or millirems (1 rem = 1000 millirems)

- Safe limit = 5,000 millirems on top of background exposure

Nuclear Radiation Today

- Amount of exposure to natural radiation depends on location

- People at high elevations or in places with more rocks have more exposure

Nuclear Radiation Today

Natural Radiation Exposure per Location

Location	Radiation Exposure (Millirems/ per yr)
Tampa, FL	63.7
Richmond, VA	64.1
Las Vegas, NV	69.5
Los Angeles, CA	73.6
Portland, OR	86.7
Wheeling, WV	111.9
Denver, CO	164.6

Nuclear Radiation Today

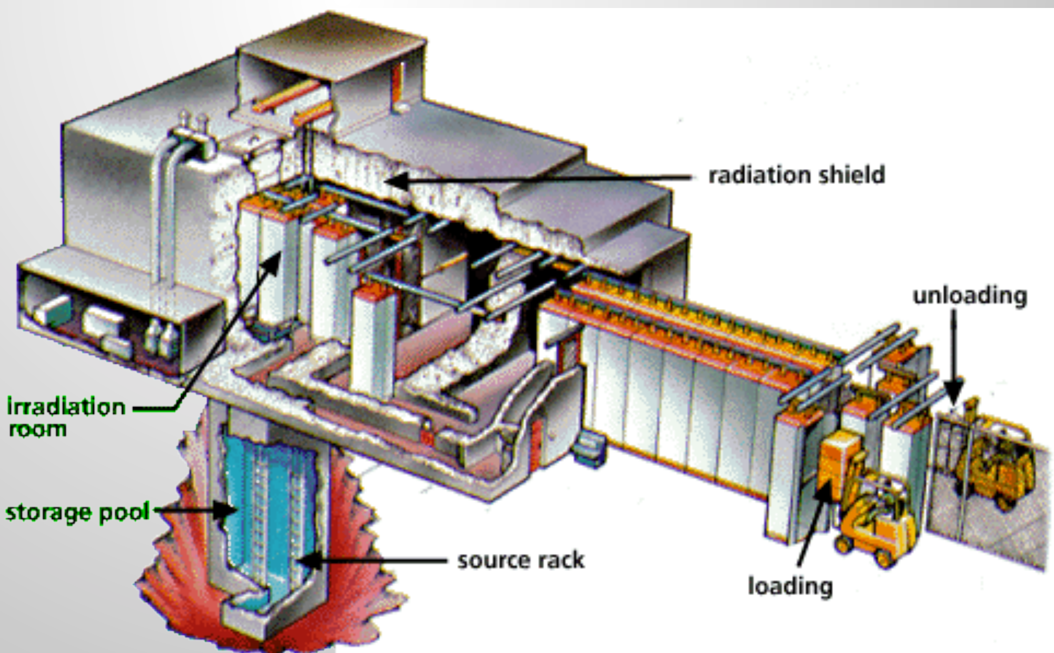
ACTIVITY	RADIATION EXPOSURE (Millirems/yr)
Smoking 1 ½ packs of cigarettes per day	8,000
Flying for 720 hours (airline crew)	267
Inhaling radon from the environment	360
Giving or receiving medical X-rays	100

Nuclear Radiation Today

- Smoke Detectors – radioactive particles produce alpha particles which in turn create an electric current
- When the current is disturbed from smoke, it sounds the alarm

Nuclear Radiation Today

- Irradiation – exposing food to radiation to kill microorganisms, bacteria, viruses, and insects



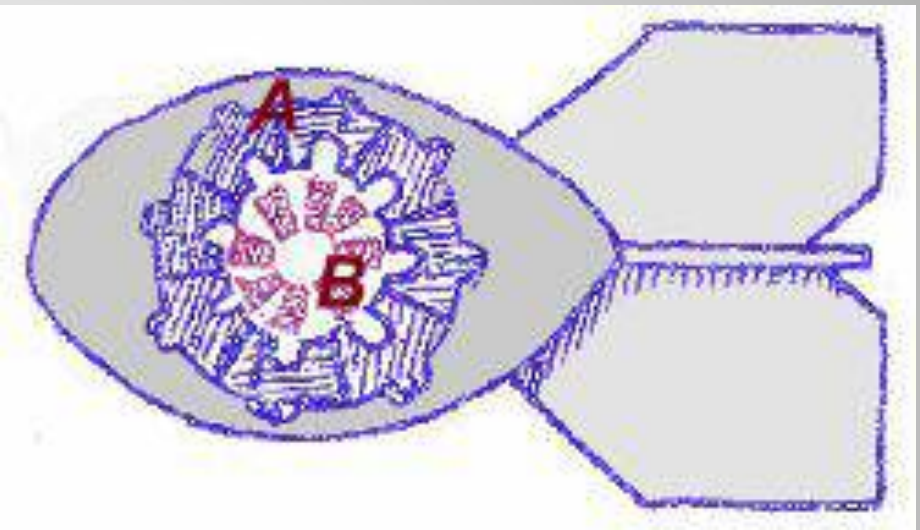
Nuclear Radiation

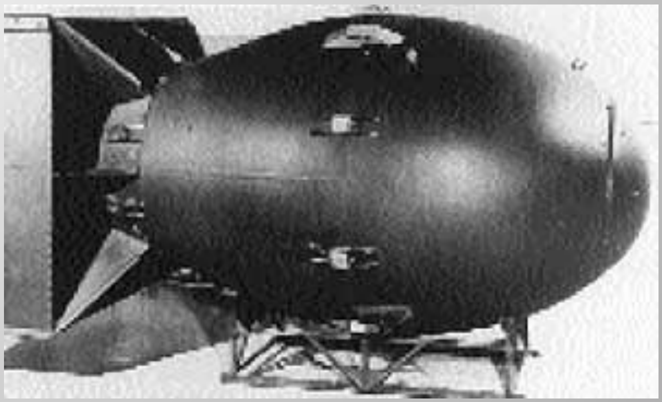
- A lot of foods you eat contain radioactive Potassium – 40

Delivers only about 18 millirem to soft tissue and 14 millirem to bone

Nuclear Bombs

- Atomic Bomb
  - Source is radioactive material like uranium or plutonium
  - Use TNT explosion to compress the plutonium core and create a critical mass
  - Within a fraction of a second, all the plutonium decays through fission and the energy of trillions of atoms is released at once

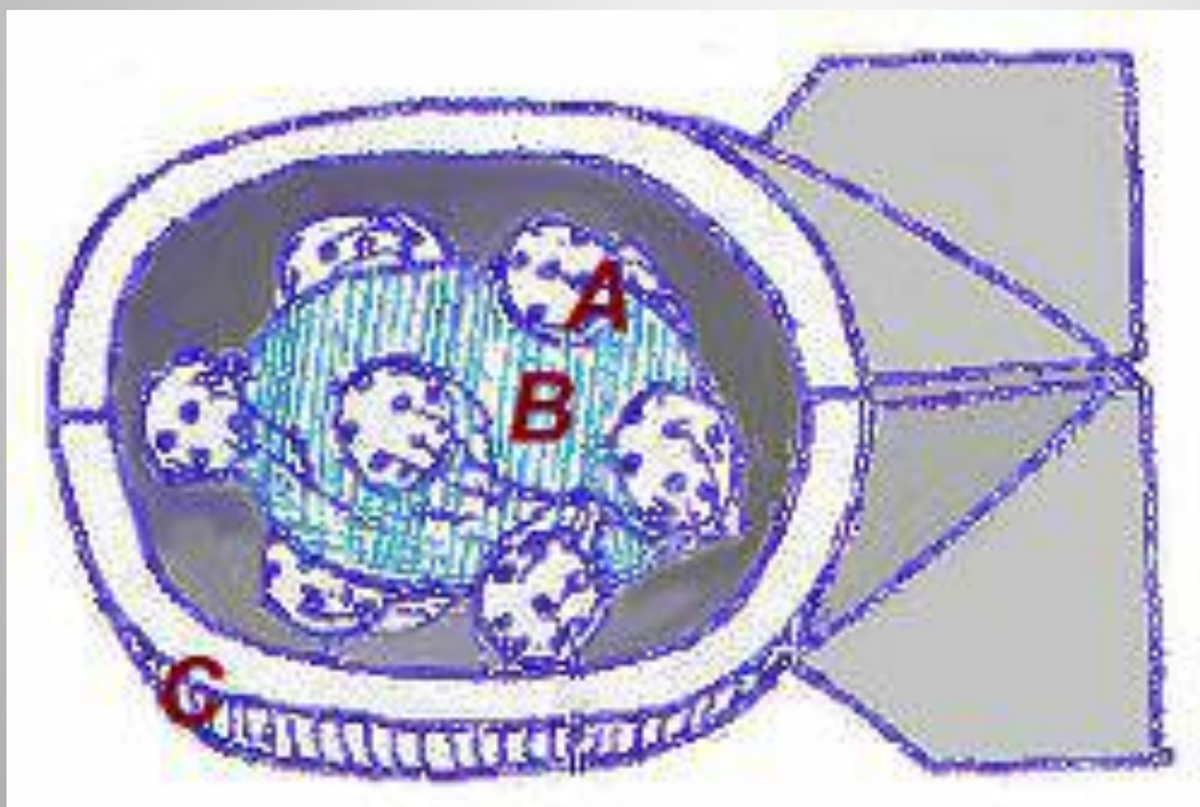




Atomic Bomb Explosions

Hydrogen Bomb

- Uses FUSION and is triggered not by TNT, but by an atomic bomb!!



Core (B) is filled with isotopes of hydrogen. Small atomic bombs surrounding the core (A) explode, causing the core to condense and undergo fusion. As the core explodes, it causes the casing (made of uranium) to undergo fission, creating more energy. In other words, an atomic bomb sets off a fusion bomb, which sets off another atomic bomb!

Hydrogen Bomb Explosion

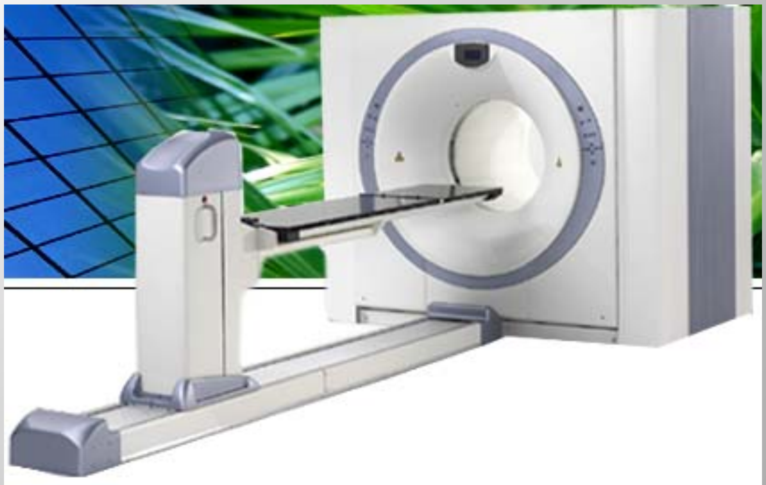
Nuclear Medicine

- The use of radioactive substances to image the body and treat disease

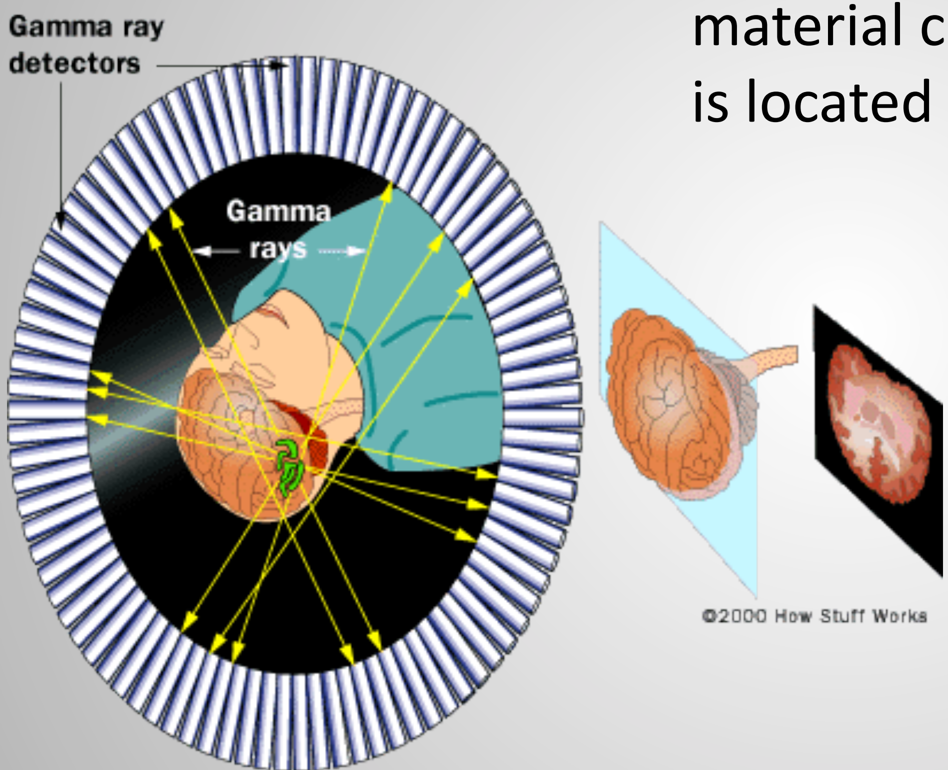
- Tests include:
  - Positron Emission Tomography (PET)
  - Single Photon Emission Computed Tomography (SPECT)
  - Cardiovascular Imaging
  - Bone Scanning

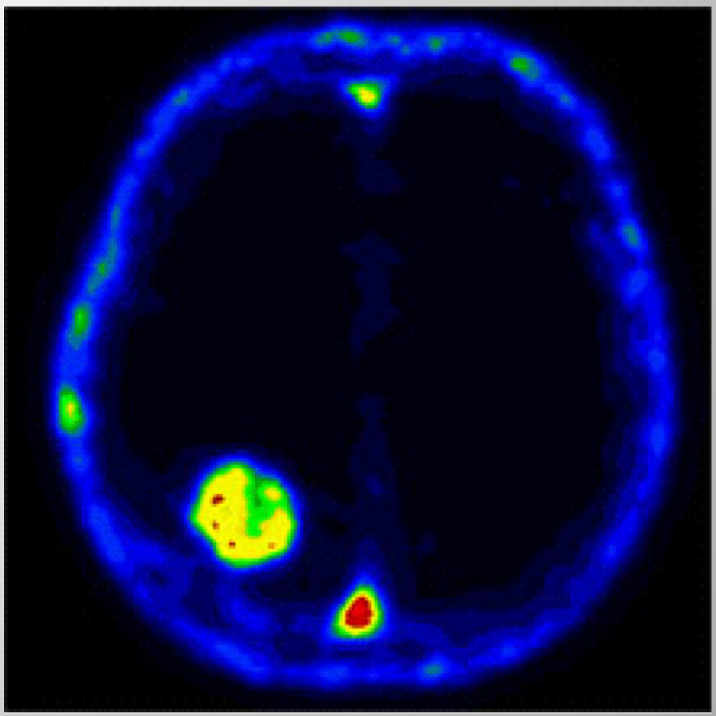
PET Scan

- Patients are injected with radioactive tracer (something that decays quickly, like Carbon-11, Nitrogen-13)
- Pet scanner detects gamma rays as the radioactive tracer decays



PET Scan
-radioactive tracer is tagged to molecule like glucose (tumors feed on blood sugar to grow) so the radioactive material concentrates where the tumor is located





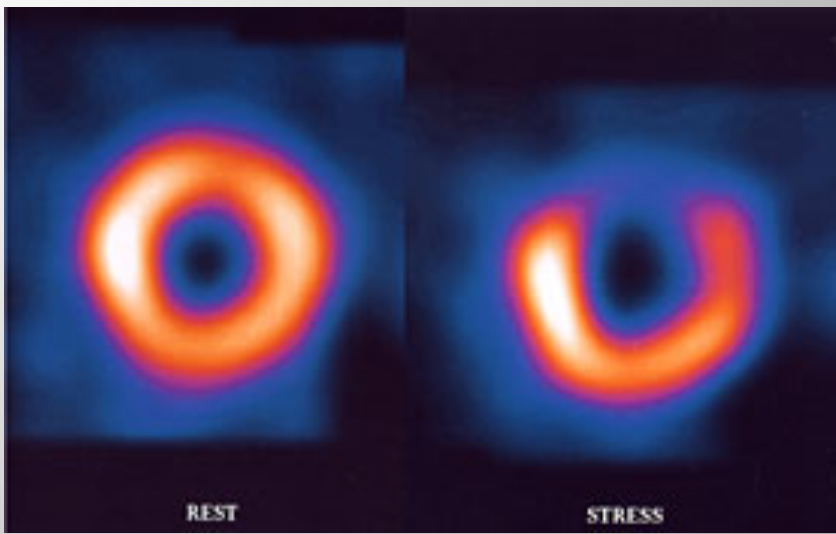
Not widely used because they need to be located near a particle accelerator that can produce the short-lived radioisotopes

SPECT Imaging

- Use radioisotopes with longer decay rates, so these are more common than PET
- Include bone scans and cardiovascular imaging

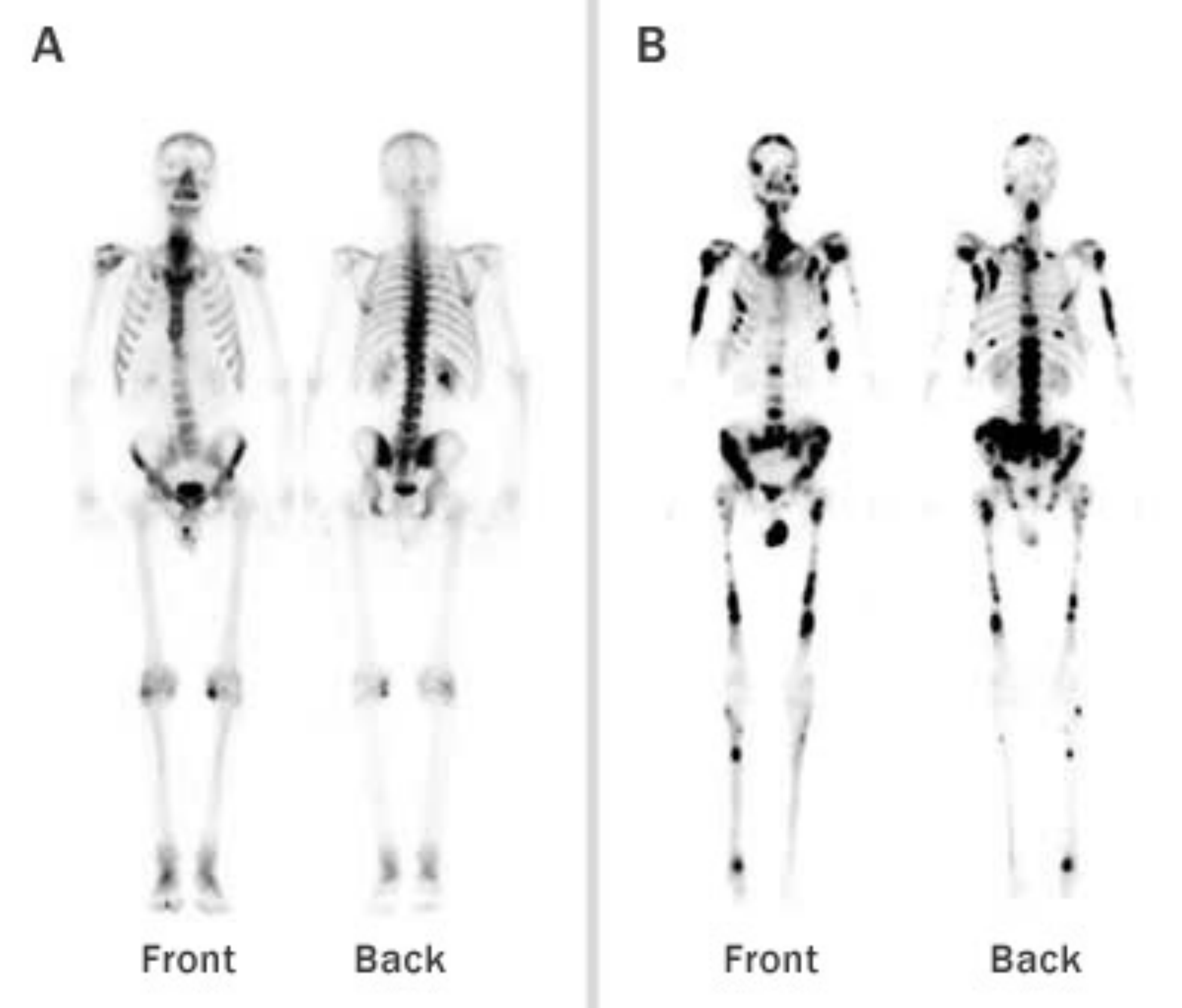
SPECT – Stress Thallium Test

- Used to test for coronary artery blockages
- Patient takes radioactive thallium, which is taken up by heart muscle. Nuclear images are taken at rest and after exercise (to test for blood flow to the heart)



SPECT – Bone Scans

- **Bone scanning detects radiation from a radioactive substances that, when injected into the body, collects in bone tissue The substance accumulates in areas of high metabolic activity, and so the image produced shows "bright spots" of high activity and "dark spots" of low activity. Bone scanning is useful for detecting tumors, which generally have high metabolic activity.**



Scan A shows hot spots (dark areas) in both knees, a sign of arthritis in this case, and a possible fracture in the second toe of the right foot. Otherwise it shows normal bone metabolism. Scan B shows numerous bone hot spots; a result of cancer that has spread to multiple locations.

Nuclear Medicine

- Are the radioactive substances used for tests harmful to the body?

- NO. They decay quickly, have lower radiation levels than an X-Ray or CT scan, and are eliminated from the body in urine or bowel movements

Biological Impact of Exposure to Radiation

- Radiation will have one of the following 3 affects on living tissue:
  - Injured or damaged cells repair themselves and have no effect on the body
  - Cells die, just as millions of cells in our body die every day and are replaced by normal healthy cells
  - Cells incorrectly repair themselves resulting in change (ie, cancer)

Biological Impact of Radiation

- Many cancers linked to high dose exposure (>50,000 mrem)
  - Leukemia, breast, liver, lung, esophagus, ovarian, stomach
- No data to prove that low doses (<10,000 mrem) will lead to cancer, but it is assumed that any exposure to radiation may pose some risk for a cancer causing effect

Biological Impact of Radiation

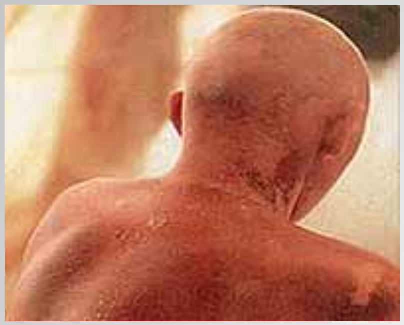
- The higher the dose of radiation the more damage is done and the sooner the effects of radiation will appear
- Acute Radiation Syndrome – person exposed to extremely high levels of radiation (80,000 – 1,600,000 mrem)

Acute Radiation Syndrome

- Initial symptoms include nausea, vomiting, and diarrhea
- Followed by swelling, itching, redness of the skin
- People who don't recover, will typically die within a few months of exposure (COD = destruction of bone marrow, which leads to infections and internal bleeding)

Acute Radiation Syndrome

A



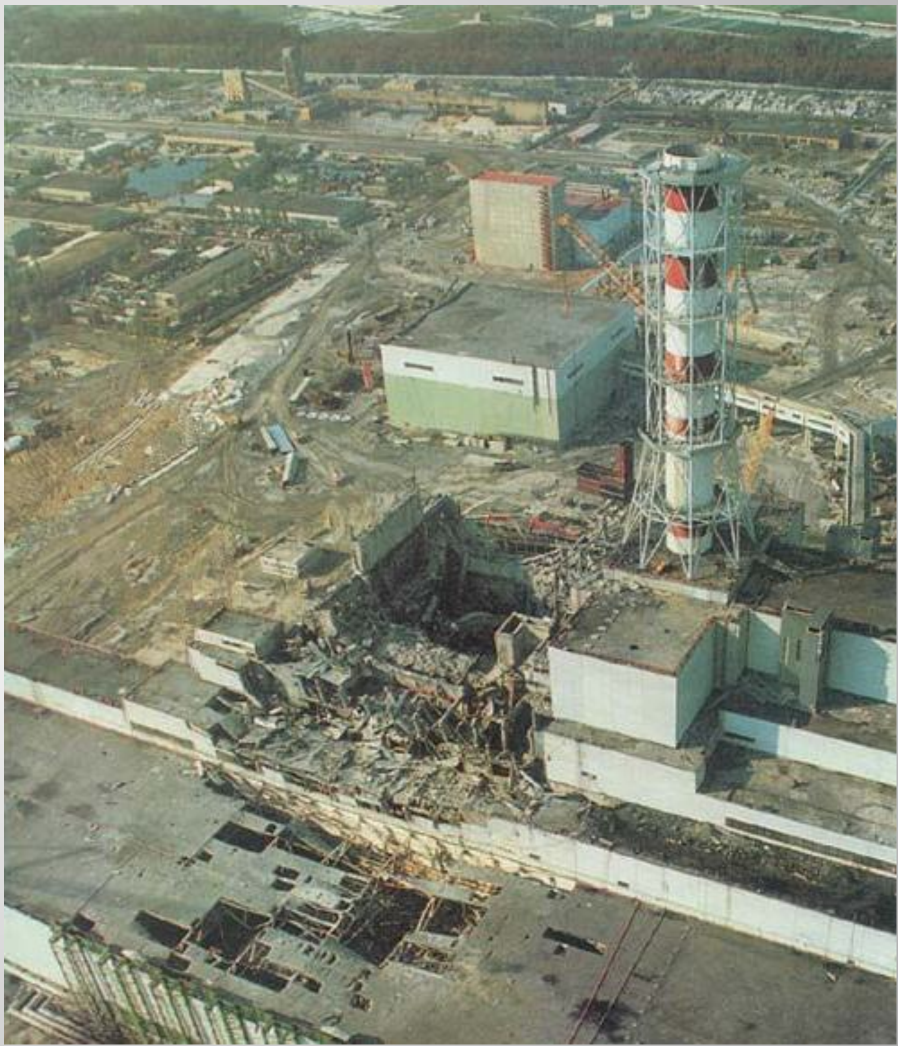
B

C

A. Man with burns on his skin after being exposed to high levels of radiation
B. Japanese woman after Hiroshima atomic bombings
C. Children were treated for ringworm in 1950 in Israel with X-Rays

Chernobyl Nuclear Disaster

- April 26, 1986, Ukraine
- Nuclear reactor blew, causing an explosion that released 400X more radiation than the atomic bomb on Hiroshima

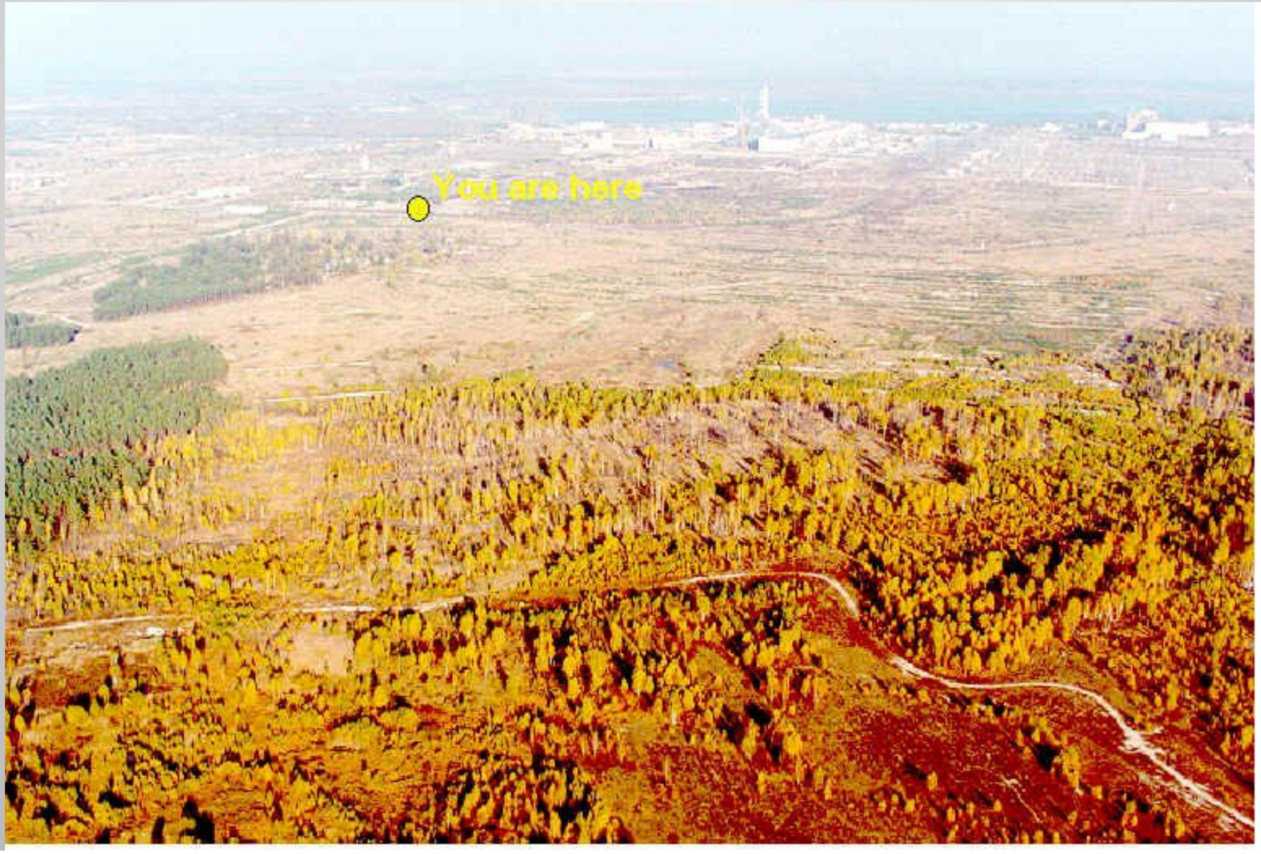


Post Chernobyl Problems

- Radioactive materials in groundwater and rivers, lakes and reservoirs were contaminated with radioactive materials

Post Chernobyl Problems

- Pine forest downwind from the reactor died and turned brownish-red, and became known as the Red Forest



Post Chernobyl Problems

- Many cattle and domestic animals nearby died of thyroid cancer
- 234 people suffered from ARS, 31 dying within a month
- 10,000 cases of thyroid cancer, another 50,000 expected
- Birth defects in children born after the explosion

Post Chernobyl Problems

Child born in the Ukraine without lymph nodes